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Variable Stars in the Open Cluster NGC 7044

by

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ABSTRACT

We present results of a search for variable stars in the intermediate-age open cluster NGC 7044. We found 23 variable stars in the observed field. One star turned out to be of the δ Sct type with two pulsational modes excited. From the position in the color-magnitude diagram we conclude that this star is a member of the cluster. Moreover, we found 13 eclipsing systems, of which five are W UMa stars, one is a β Lyr variable, six are β Per binaries showing detached configuration, and the last one is another probable β Per system. Using the period-luminosity-color relation for W UMa stars we established the membership of the contact binaries, finding four of them to be very probable cluster members. We estimated from these four stars an apparent distance modulus $(m - M)_V$ of NGC 7044 to be 14.2 ± 0.4 mag, which is smaller than previous determinations of this parameter. We were able to derive orbital period for only four β Per systems. For the remaining ones we observed only two or three eclipses. Finally, nine stars we found to show irregular light changes. Most of them are red stars not belonging to the cluster. For the cluster core we determined a reddening map, which allowed us to construct a dereddened color-magnitude diagram of NGC 7044 with a narrow main-sequence. By fitting a theoretical isochrone to this diagram we derived $E(V - I_C) = 0.92$ mag, $(m - M)_V = 14.45$ mag and $\log(\tau/\mathrm{yr}) = 9.2$.

1. Introduction

NGC 7044 ($\alpha = 21^\mathrm{h}13^\mathrm{m}09^\mathrm{s}$, $\delta = 42°29'42''$) is an intermediate-age open cluster located in a dense region of the Milky Way in Cygnus. Because of its faintness it remained unstudied for a very long time. The first modern study of NGC 7044 was published by Kałużny (1989). From the BV CCD photometry, Kałużny (1989) determined the reddening, $E(B - V) = 0.74$ mag, an approximate distance of about 4 kpc and the age of about 1.5 Gyr. The next CCD observations of NGC 7044 were obtained by Aparicio *et al.* (1993). They derived different cluster parameters: $E(B - V) = 0.57$ mag, distance 3 kpc and age 2.5 Gyr. Moreover, from the color-color diagram they estimated cluster metallicity [Fe/H] = 0. Finally, Sagar and Griffiths (1998a) presented BVI observations of NGC 7044 and obtained $E(B-V) = 0.7$ mag, $E(V - I) = 0.88$ mag, the same distance as Aparicio *et al.* (1993) and an age of 1.6 Gyr by isochrone fitting to the cluster color-magnitude diagram.

Kałużny (1989) and Sagar and Griffiths (1998a) noticed relatively wide main sequence of NGC 7044 and attributed its origin to variable reddening or large number of binaries in the cluster field. The mass function of NGC 7044 and four other open clusters was determined and studied by Sagar and Griffiths (1998b). A comparison of all photometric observations mentioned above was done by Sagar and Griffiths (1998a). They concluded that the data of Aparicio *et al.* (1993) differ systematically both in color and magnitude from the observations of Kałużny (1989) and Sagar and Griffiths (1998a) which agree with each other.

Until now the cluster was not a subject of a search for variable stars. In this paper we present our time-series observations of NGC 7044 and announce discovery of 23 variable stars in the cluster field.

2. Observations and Reductions

The observations presented here were obtained at the Białków Observatory of the University of Wrocław using a 60-cm Cassegrain telescope equipped with Andor DW432-BV back-illuminated CCD camera. One $12.8\times$ 11.7 arcmin^2 field centered on NGC 7044 was observed through V and I_C filters of the Johnson-Kron-Cousins $UBV(RI)_\mathrm{C}$ photometric system.

The observations were carried out on 26 nights between 2005 August 4 and September 25. Because we did not have an autoguider, the exposure times were rather short, amounting to only 100 s. In total, we collected 1924 and 703 CCD frames of NGC 7044 in the V and I_C passbands, respectively. On most nights the weather was very good. The seeing changed over a rather wide range, with a typical value of 2.5 arcsec.

The pre-processing of the frames was performed in the usual way and consisted of subtracting bias and dark frames and applying the flat-field correction. The I_C-filter frames were also corrected for the fringing pattern.
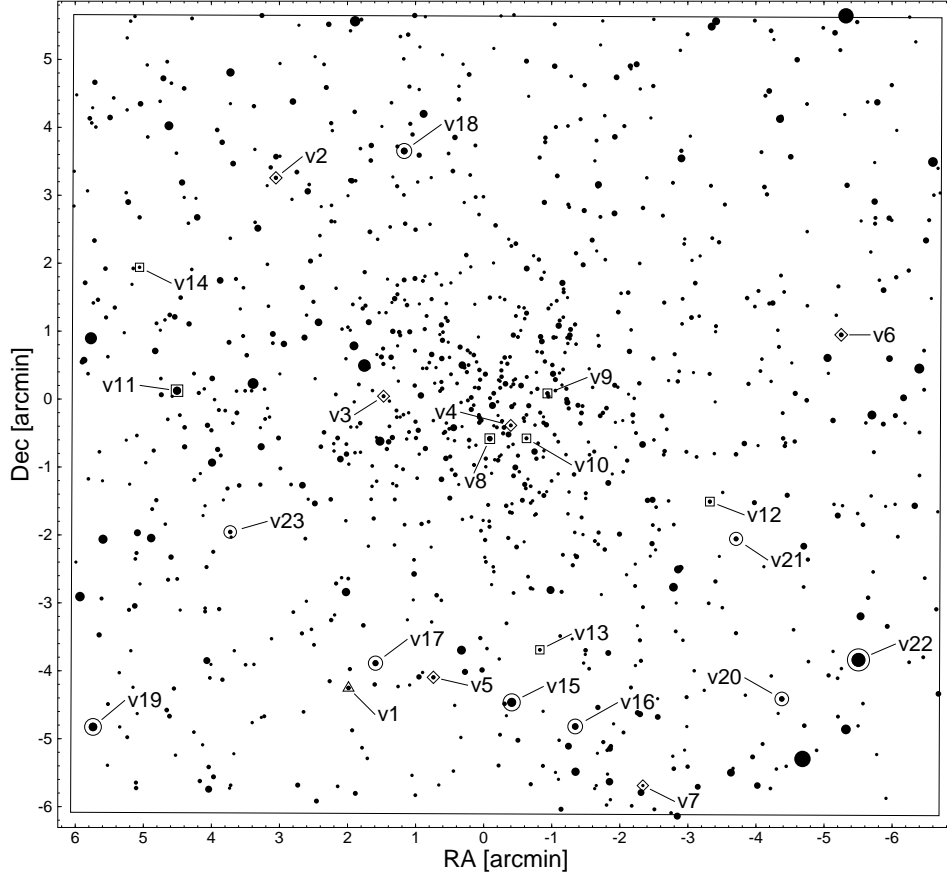
Fig. 1. Schematic view of the observed field of NGC 7044. For clarity, only stars brighter than 18 mag in V are shown (filled circles with diameter proportional to brightness). Variable stars are additionally indicated with open symbols, one δ Sct star, with a triangle, W UMa and β Lyr binary systems, with diamonds, β Per systems, with squares, and irregular variable stars with circles. Equatorial coordinates of the $(0, 0)$ point are $\alpha = 21^{\mathrm{h}}13^{\mathrm{m}}09^{\mathrm{s}}$, $\delta = 42°29'42''$.

Instrumental magnitudes for all stars in the field were computed using the DAOPHOT profile-fitting software (Stetson 1987). All images were reduced in the same way as described by Jerzykiewicz *et al.* (1996). We identified 4800 stars in the V-band reference frame of the observed field, but only about 2800 of them had photometry of reasonable quality. A finding chart for the field we monitored is shown in Fig. 1. For clarity, we show only stars brighter than 18 mag in V.

The differential photometry was derived on frame-to-frame basis rather than on the usual star-to-star basis. That is, instrumental photometry for each frame was shifted to the same magnitude scale (defined by means of a reference frame) by an average offset in brightness between a given frame

and the reference frame. The average offset was determined from a large number of bright unsaturated stars; σ-clipping was applied in order to reject deviating stars. In this way slightly different set of comparison stars was used for each frame, but the magnitude offsets are very accurate because they were computed as mean values.

Our average instrumental magnitudes and colors were transformed to the standard system using the photometric data of Sagar and Griffiths (1998a). From 760 bright stars in common with Sagar and Griffiths (1998a) we obtained the following transformation equations:

$$\begin{aligned} V - v &= -0.027\,(v - i) - 0.751, & \sigma &= 0.031, \\ V - I_{\mathrm{C}} &= +0.995\,(v - i) + 0.509, & \sigma &= 0.039, \end{aligned}$$

where uppercase letters denote standard magnitudes and lowercase letters, the instrumental magnitudes; σ is the standard deviation of the fit.

Individual instrumental V- and I_{C}-filter magnitudes of the periodic variable stars were transformed to the standard system in the following way. For each variable and both filters, phased light-curves were decomposed into Fourier series with the number of harmonics fixed at a value that gave a satisfactory fit. The quality of the fit was judged by eye. Next, instrumental magnitudes were transformed to the standard ones using the above-given equations and the color indices defined as a difference of these two smooth curves at the appropriate phase of variation.

In order to search for periodic variable stars in the observed field, for each star we computed Fourier amplitude spectrum in the frequency range from 0 to 40 d^{-1}. We looked at the light curves of all stars with significant signal-to-noise ratio of the hightest peak in the spectrum. Moreover, the light curves of all bright stars were checked manually for the presence of eclipses. This analysis resulted in finding 23 variable stars not known previously in the field of NGC 7044.

3. Variable stars

Among the 23 variable stars we detected there is one δ Sct star, 13 eclipsing systems and nine irregular variables. On the basis of the period and the light-curve shape we distinguished among eclipsing systems five W UMa stars, one β Lyr system, six β Per binaries showing indication of detached configuration and one possible β Per system. We denote these stars v1 through v23. Their photometric parameters are given in Table 1. For each variable we provide the adopted designation, type of variability, equatorial coordinates, (α, δ), mean brightness in V, mean color index $(V - I_{\mathrm{C}})$, the ranges of variability, ΔV and ΔI_{C}, and where possible, period(s), P. Periods

<center>T a b l e 1</center>

<center>Photometric data for variable stars in NGC 7044</center>

Var	Type	α_{2000} [$^{\rm h\ m\ s}$]	δ_{2000} [$^{\circ\ \prime\ \prime\prime}$]	V [mag]	V-$I_{\rm C}$ [mag]	ΔV [mag]	$\Delta I_{\rm C}$ [mag]	P [d]
v1	δ Sct	21 13 19.74	42 25 26.8	16.838	1.423	0.029	0.022	0.088957
						0.017	–	0.091464
v2	W UMa	21 13 25.56	42 32 57.4	17.158	1.413	0.117	0.105	0.33388
v3	W UMa	21 13 16.97	42 29 44.5	17.642	1.414	0.421	0.397	0.46057
v4	W UMa	21 13 06.83	42 29 18.7	17.745	1.558	0.559	0.535	0.50363
v5	W UMa	21 13 12.99	42 25 36.2	17.097	1.447	0.470	0.456	0.61501
v6	W UMa	21 12 40.49	42 30 38.7	16.616	1.411	0.269	0.263	0.65472
v7	β Lyr	21 12 56.32	42 24 00.6	18.504	1.281	0.393	0.349	0.87539
v8	β Per	21 13 08.50	42 29 07.0	15.790	2.034	0.12	0.08	1.83882
v9	β Per	21 13 03.90	42 29 47.0	16.944	1.450	0.39	0.37	2.5269
v10	β Per	21 13 05.58	42 29 07.3	17.505	1.622	0.17	0.18	2.9056
v11	β Per	21 13 33.43	42 29 49.4	13.943	1.205	0.09	0.08	4.1528
v12	β Per	21 12 50.97	42 28 11.4	17.174	1.443	0.52	0.27	–
v13	β Per	21 13 04.52	42 26 00.5	17.940	1.677	0.26	0.11	–
v14	β Per	21 13 36.43	42 31 38.4	18.158	1.949	0.43	0.27	–
v15	Irr	21 13 06.76	42 25 14.1	13.406	3.248	0.09	0.06	–
v16	Irr	21 13 01.70	42 24 52.8	14.932	2.929	0.08	0.05	–
v17	Irr	21 13 17.60	42 25 48.7	15.378	1.055	0.06	0.04	–
v18	Irr	21 13 15.33	42 33 21.1	14.721	3.260	0.10	0.05	–
v19	Irr	21 13 40.09	42 24 52.4	13.587	3.785	0.20	0.07	–
v20	Irr	21 12 45.26	42 25 17.1	15.759	3.747	0.25	0.09	–
v21	Irr	21 12 48.88	42 27 38.5	16.200	5.641	0.19	0.15	–
v22	Irr	21 12 39.15	42 25 51.6	11.326	3.009	0.20	0.09	–
v23	Irr	21 13 29.18	42 27 44.6	16.840	5.264	0.70	0.41	–

are given with an accuracy resulting from a non-linear least-squares fit of truncated Fourier series to the observations.

3.1. The δ Sct star

Star v1 shows sinusoidal brightness variations in both filters, with the amplitude in V greater than in $I_{\rm C}$. Fourier analysis of the V-filter observations revealed frequency $f_1 = 11.241$ d^{-1} (see Fig. 2a). After prewhitening the data with f_1, another peak, corresponding to frequency $f_2 = 10.934$ d^{-1} appeared in the amplitude spectrum (see Fig. 2b). It should be noted that due to the daily aliasing, the secondary frequency may be incorrect by 1 d^{-1}. The strongest alias of f_2 frequency, $f_2 + 1$ d^{-1}, has almost the same amplitude. Fitting the sum of sine terms with f_1 and f_2 or its alias to the original data gives almost the same standard deviation of 0.027 mag. It is therefore difficult to conclude which secondary frequency is the true one. Further observations of this star are needed to resolve this ambiguity.
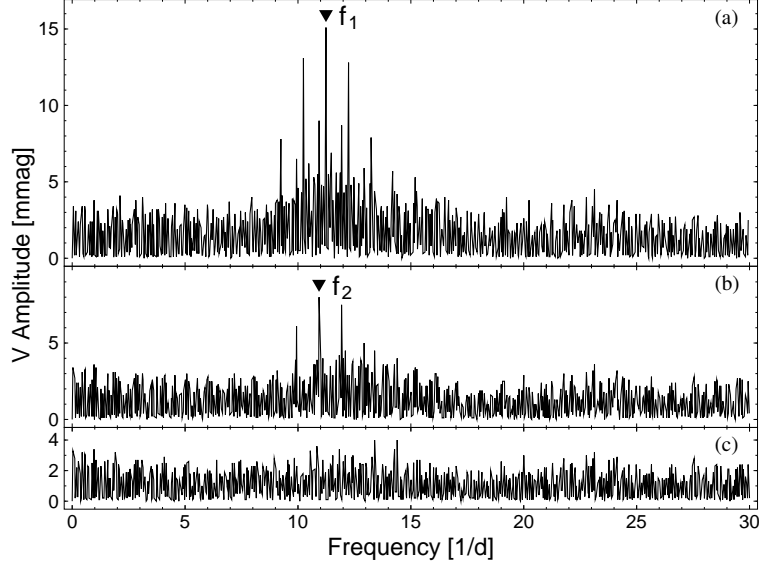
Fig. 2. Fourier amplitude spectra of the δ Sct type star v1: (a) for original V-filter observations, (b) after prewhitening with frequency $f_1 = 11.241$ d^{-1}, and (c) after removing terms with frequencies f_1 and $f_2 = 10.934$ d^{-1}. The ordinate scale is the same in *all panels*.
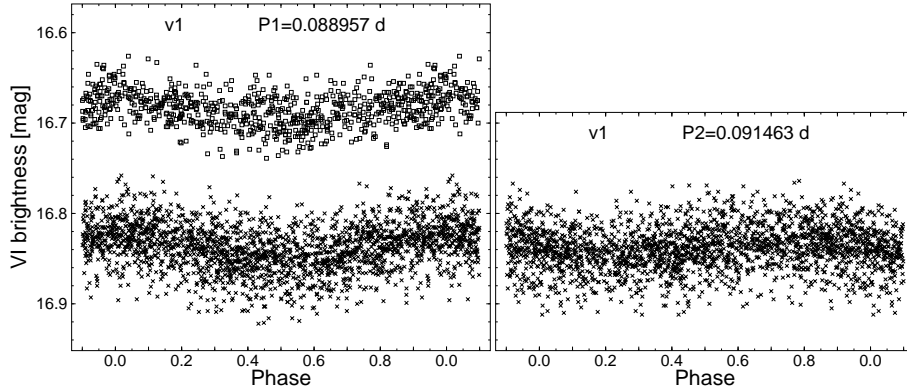

Fig. 3. V (crosses) and I_C (squares) light-curves of the δ Sct star v1. The *left panel* shows the residuals obtained after removing the f_2 component, phased with the period P_1. The *right panel* shows the data prewhitened with f_1 and phased with the period P_2. Initial epoch was chosen arbitrarily, but it is the same for each light curve. The ordinate scale is the same in *both panels*.

We may, however, safely classify v1 as a δ Sct star showing at least two frequencies.

The amplitudes of both sinusoidal components detected in v1 are given in Table 1. We were able to find only the primary frequency in the I_C-filter observations of this star. The phase diagrams of the two pulsational
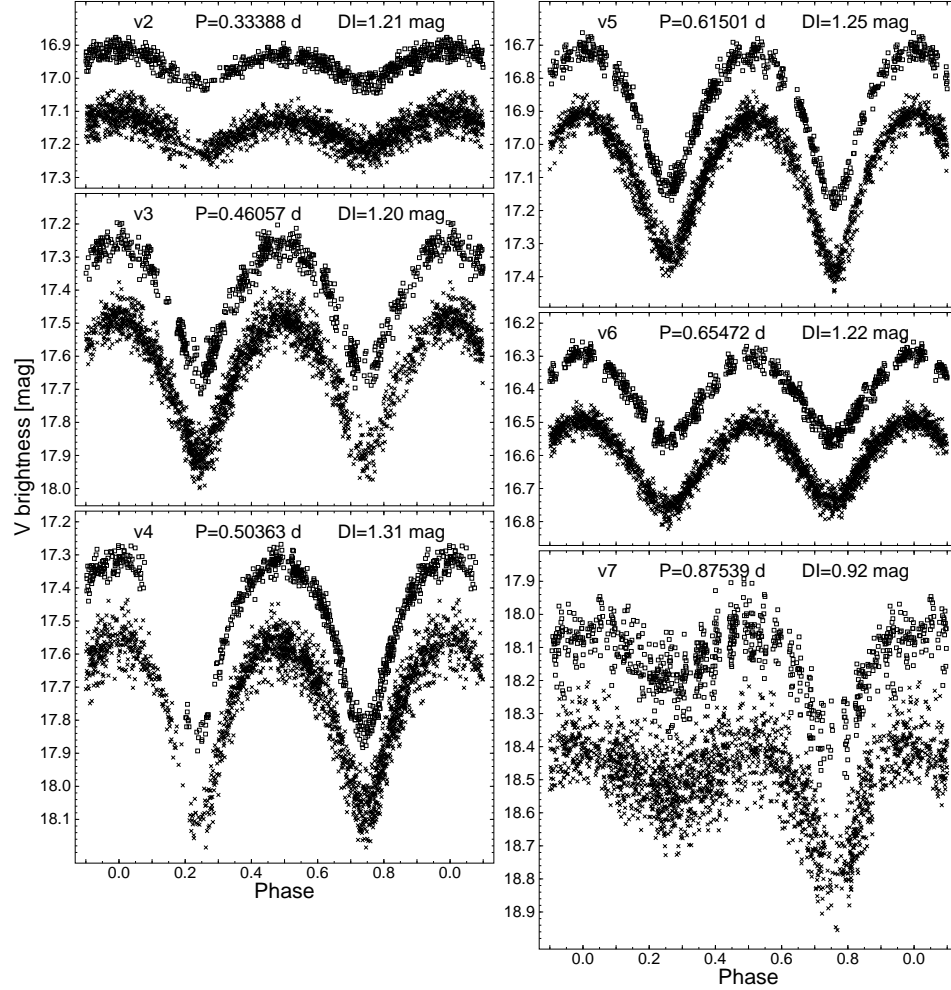
Fig. 4. *V* (crosses) and I_C (squares) light-curves of W UMa (v2 – v6) and β Lyr (v7) stars detected in the field of NGC 7044. DI is a magnitude shift applied to the I_C data. The ordinate scale is the same in *all panels*.

components of v1 are shown in Fig. 3.

Judging from the position of v1 in the color-magnitude diagram (see Fig. 11) we may assume that the star is a cluster member. Using this fact we can determine its absolute magnitude. We adopted the values of distance modulus $(m - M)_V$ and reddening $E(B - V)$ for NGC 7044 from Kałużny (1989) and Sagar and Griffiths (1998a). In both cases the resulting absolute brightness M_V of v1 (1.5 mag and 2.2 mag, respectively) places the star in the classical instability strip. This further supports our classification of v1 as a δ Sct star.
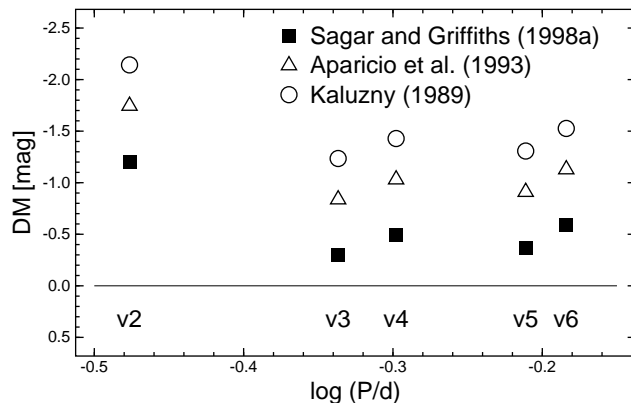
3.2. W UMa and β Lyr binaries

Fig. 5. Period-luminosity relation for W UMa type stars in the field of NGC 7044. DM is the difference between absolute brightness calculated from the apparent V-magnitude and cluster parameters derived by Sagar and Griffiths (1998a, filled squares), Aparicio *et al.* (1993, triangles), and Kałużny (1989, circles) and the magnitude calculated from Ruciński's (1994) relationship.

The VI_C light curves of five W UMa type (v2 – v6) and one β Lyr type (v7) stars are presented in Fig. 4. As can be seen from the figure, the depths of the eclipses in v2 are significantly lower than in other W UMa systems we observed. The large scatter in the phase diagram of v7 comes from the fact that it is a very faint star ($V = 18.5$ mag). The location of this variable on the blue side of the main sequence in the color-magnitude diagram (see Fig. 11) suggests that v7 is not a member of NGC 7044.

W UMa type binary systems are known to obey a relation between their period, color and absolute brightness (Ruciński 1994, 2004):

$$M_V = -4.43 \, \log(P/\mathrm{d}) + 3.63 \, (V - I_C)_0 - 0.31,$$

where $(V-I_C)_0$ is the intrinsic color index measured at the maximum brightness of the binary system and P is the orbital period. The uncertainty of this calibration is approximately ± 0.35 mag in M_V (Ruciński and Duerbeck 1997). Because of this, the period-luminosity relation can be used only for deriving the distance to a large group of contact binaries in one stellar cluster or galaxy (for a discussion see Ruciński 2004). It can be also used as a tool for sieving out field interlopers from a sample of W UMa binaries in a given open or globular cluster (see, for example, Ruciński 2000).

We compared pairs of absolute magnitudes of W UMa stars we observed: M_{cal} computed from the relation given above and M_{obs} derived from the apparent V-magnitude and cluster distance modulus. We adopted distance moduli $(m - M)_V$ and reddenings $E(B - V)$ and $E(V - I_C)$ from Sagar and Griffiths (1998a), Aparicio *et al.* (1993), and Kałużny (1989). In calculations we assumed the reddening ratio given by Moro and Munari (2000), $E(V -$
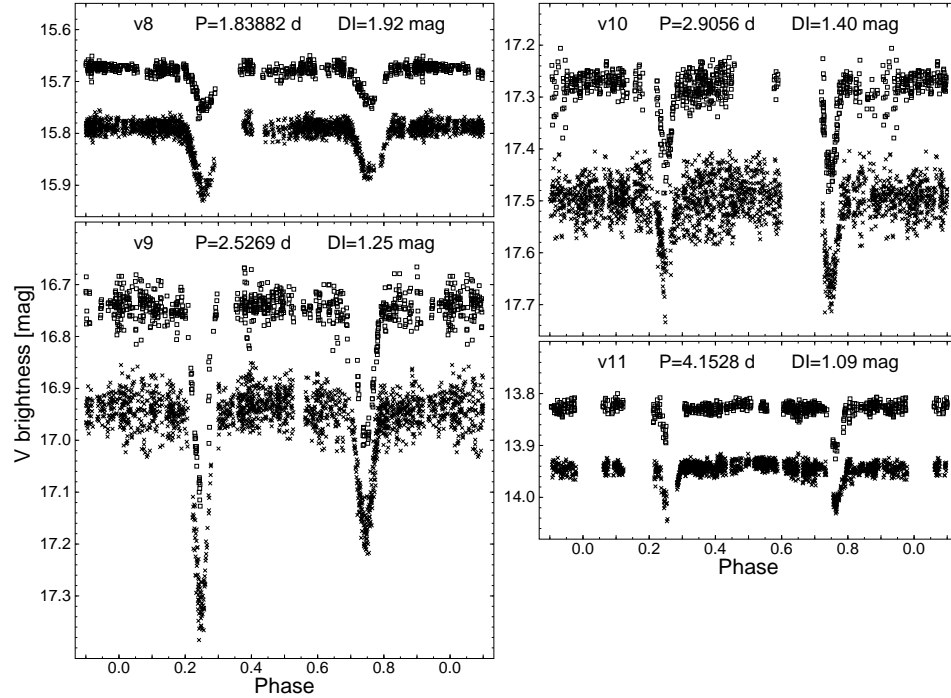
Fig. 6. V (crosses) and I_C (squares) light-curves of β Per stars in the field of NGC 7044 for which orbital period could be determined. DI is a magnitude shift applied to the I_C data. The ordinate scale is the same in *all panels*.

$I_C)/E(B-V) = 1.1$ mag. The differences $\Delta M = M_{obs} - M_{cal}$ are plotted against the logarithm of orbital period in Fig. 5.

From Fig. 5 one can see a large spread of distance moduli (and reddenings) determined for the cluster by different authors. Only photometry of Sagar and Griffiths (1998a) agrees reasonably well (within limits of accuracy of the Ruciński's (1994) calibration) with the period-luminosity relation. More importantly, among each group of brightness differences (defined by a set of cluster parameters), stars v3, v4, v5, and v6 have similiar values of ΔM, while the value for v2 is approximately 0.9 mag smaller. Consistent results for v3 – v6 allow us to conclude that these binaries are members of NGC 7044, whereas v2 is a foreground star. It should be also noted that all observed W UMa systems are located on the main sequence in the color-magnitude diagram shown in Fig. 11.

The mean distance modulus $(m - M)_V$ of NGC 7044 derived from the four W UMa stars assumed to be cluster members is $14.2 \pm 0.1 \pm 0.35$ mag (where 0.1 mag is the r.m.s. error of the mean and 0.35 mag is the uncertainty of luminosity calibration). Taking $E(B-V) = 0.7$ mag and assuming $A_V/E(B-V) = 3.0$ mag, this translates into a distance of 2.4 kpc, smaller than previous estimates but still within the range of uncertainty.
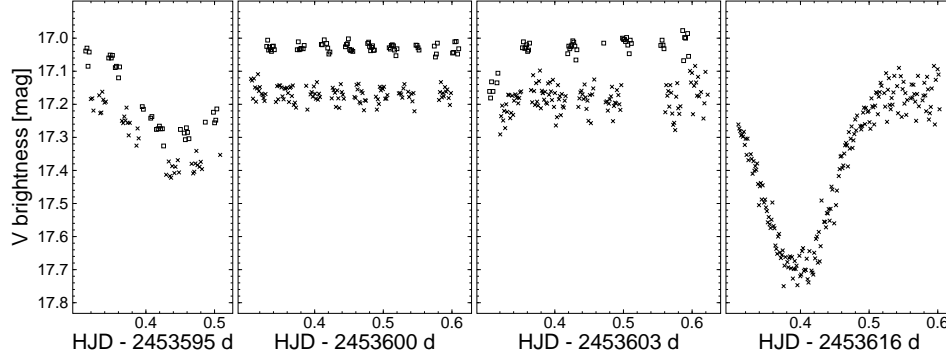
Fig. 7. *V* (crosses) and I_C (squares) observations of v12 on four nights showing evidence for three eclipses (*first, third* and *fourth panel*). The *second panel* shows an example of a night outside eclipse. I_C magnitudes were shifted by 1.3 mag.
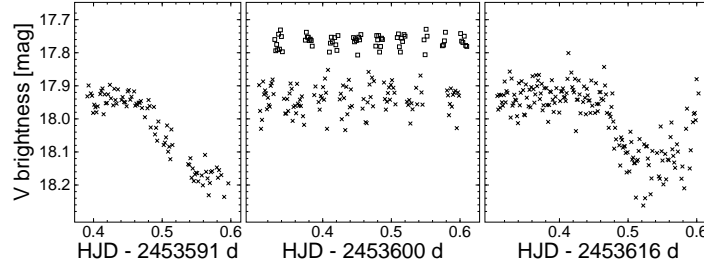

Fig. 8. *V* (crosses) and I_C (squares) observations of v13 on three nights showing evidence for two eclipses (*first* and *third panel*). The *second panel* shows an example of a night outside eclipse. I_C magnitudes were shifted by 1.5 mag.

3.3. β Per binaries

Six other eclipsing systems discovered in the field of NGC 7044, namely v8 through v13, we classify as β Per stars. These binaries show light variations typical for detached eclipsing binaries, that is, relatively sharp eclipses with constant brightness between them. We were able to determine orbital periods for only four of these stars (v8 – v11). Their light curves are presented in Fig. 6.

Four nights of observations of the eclipsing variable v12 are shown in Fig. 7. For this star, we observed only two eclipses with clearly defined minimum of brightness (*first* and *fourth panels* of Fig. 7) and indication for another eclipse on HJD 2453603 (*third panel* of Fig. 7). The time span *dt* between secondary (*first panel* of Fig. 7) and primary eclipses (*fourth panel* of Fig. 7) is about 20.95 d. Assuming circular orbit, the period would be $P = dt/(n+0.5)$ with n being an integer number. Only $n = 0$ folds the data into a satisfactory phase diagram. Thus, the period of v12 would be very long, amounting to about 41.9 d. However, if the eclipse, of which a part is shown in the *third panel* of Fig. 7, were a primary eclipse, we could estimate
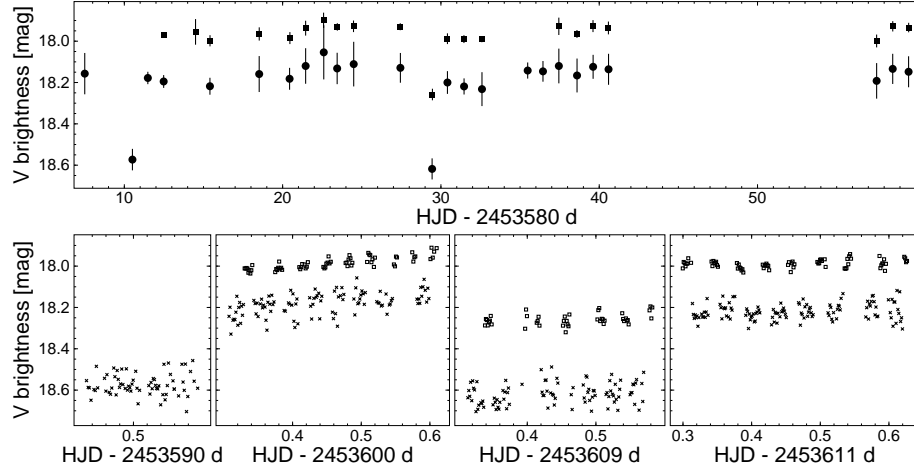
Fig. 9. *V* (crosses) and I_C (squares) observations of v14. The *upper panel* shows average nightly magnitudes with error bars of length equal to the rms errors. The *bottom panels* present four nights of observation with indication for two eclipses (*first* and *third panel*). I_C magnitudes were shifted by 1.75 mag.

the orbital period from the two primary minima with the time span of 13.17 d. In this case, the only possible period would be 13.17 d. The results of the two approaches exclude each other. This indicates that the eccentricity of the system is not zero. Further observations of this star are needed for a successful determination of its orbital period.

For the eclipsing star v13 we observed only two minima with the time difference of aproximately 25 d. They are shown in the *first* and *third panels* of Fig. 8. It is not certain of which type are these eclipses. Most probably, one is the primary and the other is the secondary. Assuming that they are separated in phase by 0.5, only long periods (50.0 and 16.67 d) give satisfactory phase diagram with no night of constant brightness falling into any of the eclipses. It is possible, however, that this is an eccentric binary system.

Another variable star which we tentatively classify as a β Lyr system is v14. The epochs of the start and the end of eclipses were not observed for this star, but the data show two eclipses, each lasting at least 5 hours. The mean nightly magnitudes of this star are shown in the *upper panel* of Fig. 9, whereas *bottom panels* of the same figure show four nights with indication for two eclipses (*first* and *third panels*). There are variations of brightness outside eclipses (see *second bottom panel* of Fig. 9) indicating the presence of proximity effects in the system. We could not determine a period for v14.

3.4. Irregular stars

The largest group of variable stars discovered in the field of NGC 7044 consists of nine irregular variables (v15 – v23). Their light curves are plotted
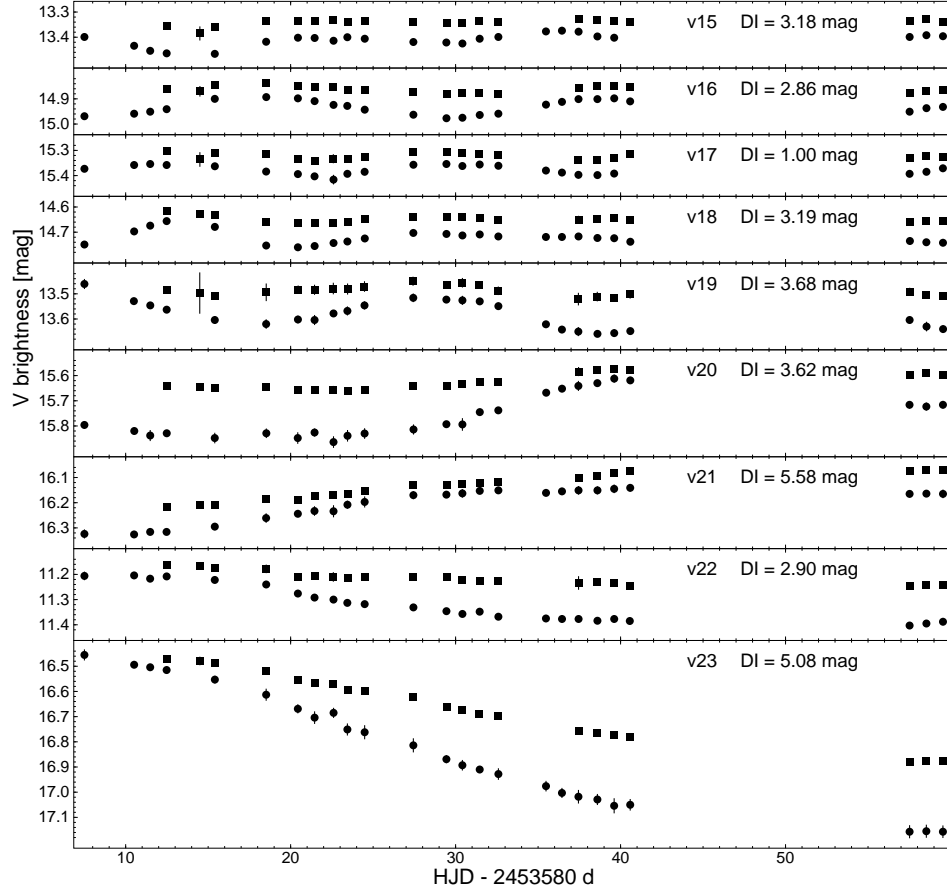
Fig. 10. V- (filled crosses) and I_C-filter (filled squares) mean nightly magnitudes of the red variable stars in the field of NGC 7044. The error bars have a length of the rms errors. DI is a magnitude shift applied to the I_C data. The ordinate scale is the same in *all panels*.

in Fig. 10. Eight of these variables are red, and one (v17) is situated on the main sequence, above the cluster's turn-off point (see Fig. 11).

4. Color-Magnitude Diagram

The V vs. $(V - I_C)$ color-magnitude diagram for the observed field of NGC 7044 using all stars with realiable photometry is shown in Fig. 11a. The two clearly visible features can be seen in this diagram: a relatively wide main sequence and a clump of red giants slightly above and about 0.5 mag to the red off the turn-off point. There is also a group of stars brighter and bluer than turn-off point, indicating that some of them may be blue stragglers.
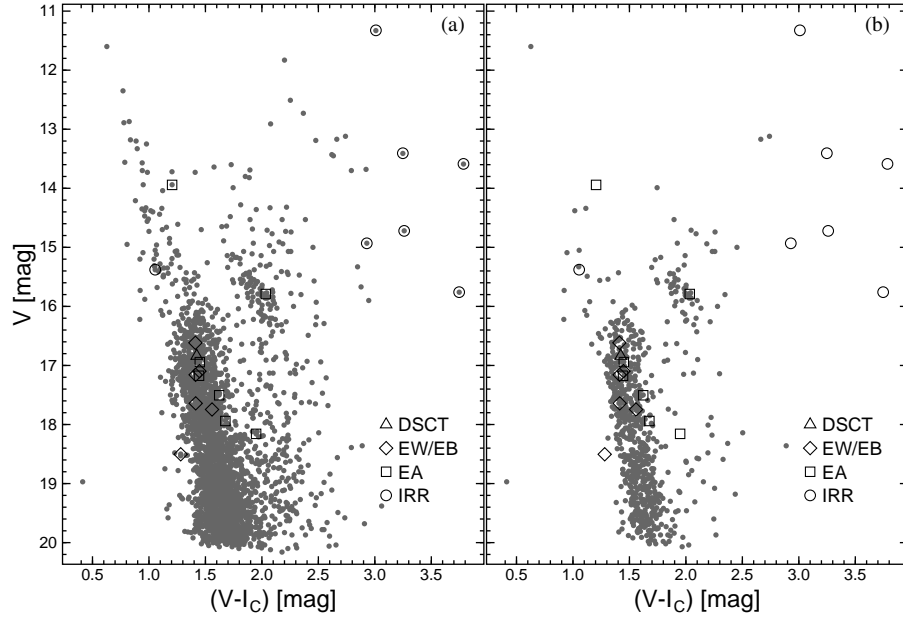
Fig. 11. The V vs. $(V - I_{\mathrm{C}})$ color-magnitude diagrams for NGC 7044: (a) using all observed stars with realiable photometric data, and (b) using only stars with the distance from cluster center smaller than the derived cluster radius of 2.5 arcmin. Variable stars are indicated with open symbols, one δ Scuti star, with a triangle, W UMa and β Lyr binary systems (EW/EB), with diamonds, β Per systems (EA), with squares, and irregular variable stars with circles (the two extremely red stars, v21 and v23, are not shown). The ordinate and abscissa scales of the *left panel* are the same as the corresponding scales of the *right panel*.

Since NGC 7044 is very close to the Galactic plane ($b \approx 4°$), the contamination by cluster non-members is rather high, especially in regions well away from the cluster center. This manifests itself in Fig. 11a mostly through the wide main sequence and a numerous group of faint stars on its red side. In order to make a rough cleaning of color-magnitude diagram from possible non-members, we determined the cluster angular diameter from the radial profile of star counts. We applied the same procedure as that described by Sagar and Griffiths (1998b) in which the cluster's center and diameter are derived iteratively. This analysis resulted in a radius of about 2.5 arcmin.

The cleaned color-magnitude diagram was constructed using only stars with distance from the cluster center smaller than the estimated cluster radius. It is given in Fig. 11b. As expected, the cluster main sequence and red giant clump are better defined in this figure in comparison to the original diagram in Fig. 11a.

We also show in Fig. 11 the location of variable stars we detected. An information on their possible membership can be inferred from their position in this diagram. The membership of W UMa and β Lyr stars was already

discussed in Chapter 2.2. Among β Per systems, two stars (v9 and v12) are located on the cluster main-sequence, two other stars (v10 and v13) are at the red border of the main sequence, and v8 is in the red giant region. These stars are very probable cluster members. Only v11 in this group seems to be a non-member. A possible β Lyr system v14 is a foreground object.

Recently, Dias *et al.* (2006) determined membership probabilities for 150 stars in the field of NGC 7044 using the UCAC2 catalogue of accurate positions and proper motions published by Zacharias *et al.* (2004). Unfortunately, the limiting V-brightness of this catalogue is 16 mag. As can be seen from Fig. 11, this is well above the cluster turn-off point. Because of that, most stars in the sample studied by Dias *et al.* (2006) are cluster non-members. In fact, the average proper motions of the assumed members (35 stars) and non-members (115) derived by Dias *et al.* (2006) are almost the same, so that distinguishing the two populations is not possible. Thus, in our opinion, membership probabilities derived by these authors are rather doubtful.

Among stars analyzed by Dias *et al.* (2006) we find five variable stars, v8 (membership probability 12 %), v11 (41 %), v16 (61 %), v17 (3 %), and v21 (86 %). These values mostly do not agree with information on membership derived from our photometry. The very evident example is the red variable v21, which is a highly probable cluster member according to Dias *et al.* (2006), but from the photometric point of view it is definitely not a member.

5. Reddening Map and Cluster Parameters

In order to verify variable reddening in NGC 7044, we calculated a map of reddening in central region of the observed field using the procedure described by Pigulski and Kołaczkowski (1998). The method assumes that all measured extinction is caused by matter lying between the cluster and the observer and that it changes smoothly over the field. These assumptions imply that differences in color of member stars lying very close to each other are intrinsic, and not due to differences in reddening.

We selected a sample of very probable cluster members, that is, stars from or close to the cluster main sequence, with distance from the cluster center $r < 2.5$ arcmin, brightness $V > 16.7$ mag, and $(V - I_{\rm C})$ colors from 1.3 to 1.8 mag. For a fiducial line used in the color excess calculations, we adopted the isochrone of Girardi *et al.* (2000) with $\log(\tau/{\rm yr}) = 9.1$, shifted in color by 1 mag and in brightness by 15.1 mag. The assumed scale of color changes was 25 pixels, corresponding to about 0.2 pc at the cluster distance. In an iterative process we first calculated the reddening map (an average color excess as a function of position in the observed field) and next rejected
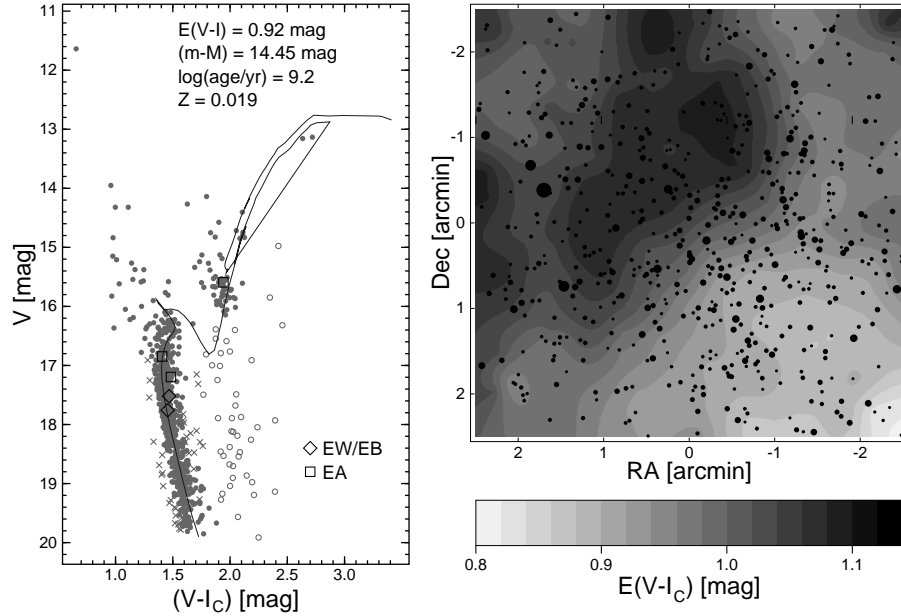
Fig. 12. The V vs. $(V - I_C)$ color-magnitude diagram of NGC 7044 corrected for the effect of variable reddening (*left panel*) and the reddening map (*right panel*) showing the distribution of the $E(V - I_C)$ color excess across the cluster field. The reddening map covers the central 5×5 arcmin^2 of NGC 7044. Only stars from this area are shown in the color-magnitude diagram. Very probable field stars are indicated with open circles and stars found in the reddening map derivation to be cluster non-members are shown with crosses. The best-fitting isochrone of Girardi *et al.* (2000) for the marked values of color excess, distance modulus and age is shown as solid line. Several variable stars are indicated with open symbols, W UMa and β Lyr binary systems (EW/EB) with diamonds, β Per systems (EA) with squares. The ordinate and abscissa scales of the *left panel* are the same as the corresponding scales in Fig. 11.

stars with color excesses deviating from the average value, counting these stars as probable cluster non-members.

The reddening map is shown in the *right panel* of Fig. 12. The $E(V-I_C)$ ranges from 0.83 to 1.13 mag; the average value is 0.90 mag. The color-magnitude diagram corrected for the effect of variable reddening is presented in the *left panel* of Fig. 12. In comparison with Fig. 11, the main sequence is thinner and the turnoff point better defined.

We attempted fitting of the theoretical isochrones by Girardi *et al.* (2000) to the corrected color-magnitude diagram by eye. These isochrones include the effects of core overshooting and mass loss on the red giant branch. We assumed solar metallicity. The best fit was achieved for the following set of parameters: $E(V-I_C) = 0.92$ mag, $(m-M)_V = 14.45$ mag and $\log(\tau/\text{yr}) = 9.2$. The isochrone corresponding to the above parameters is shown with the

solid line in the *left panel* of Fig. 12. As can be seen from the figure, the isochrone does not fit the group of red giants very well. The same problem was encountered by previous investigators of the cluster. It may be probably explained by the deficiencies of input physics of theoretical stellar models. Following the suggestion of Sagar and Griffiths (1998a), we also tried to fit metal-poor isochrones to the color-magnitude diagram of NGC 7044, but the quality of fit was still unsatisfactory.

Our cluster parameters are not very different from the values obtained by Sagar and Griffiths (1998a). The distance modulus derived by us is 0.15 mag smaller than the value of Sagar and Griffiths (1998a). This was, however, to be expected because our VI_C photometry is tied to the photometric data of Sagar and Griffiths (1998a) through the transformation equations (see Chapter 2). The small differences come probably from the fact that our color-magnitude diagram has been corrected for the effect of variable reddening and from using a different set of isochrones. In comparison to distance modulus of Sagar and Griffiths (1998a) our value from isochrone fitting is closer to that derived by us from W UMa stars (Paragraph 3.2), but agreement is still far from satisfactory.

It should be noted that Sagar and Griffiths (1998a) fitted isochrones to the blue edge of the original broad main sequence and concluded that a significant fraction of cluster members are binaries. Our results indicate that the cluster main sequence corrected for differential reddening can be reasonably well described with a population of mostly single stars.

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